Superconducting Quantum Phase Transitions

Scientific Achievement

The high interest in the physics of a quantum critical point (QCP) is motivated by the explosive growth of its experimental realizations, driving, in turn, the quest for a theoretical understanding of quantum phase transitions (QPT). The challenge for theory is two fold: First, we must identify experimentally accessible systems with QPT. Second, these systems should serve as platforms for a systematic and comprehensive theoretical description of QPT.

We propose an exemplary realization of the QCP in dirty superconducting samples of reduced dimensions under the application of an external magnetic field parallel to a film (or a nanowire) that allows complete experimental exploration of the vicinity of the QCP on the one hand and systematic theoretical study on the other.

We investigated the fluctuation correction to the normal state conductivity in the vicinity of a parallel-field-induced QCP taking into account both, quantum and thermal fluctuations within the diagrammatic perturbation theory. Our key finding is that there are three regimes that show qualitatively different behaviors ranging from quantum to classical. The particular temperature and field behavior of the conductivity is dictated by the chosen pathway in approaching the QCP. We found that for a nanowire (or a hollow cylinder) as well as for a thin film, the zero temperature conductivity correction that governs the quantum regime, is negative, which means that the quantum pairing-fluctuations increase the resistance to the charge flow. Our findings predict that experiments should detect a negative magnetoresistance in the quantum regime.

Significance

We obtained novel important physical results concerning fluctuation conductivity behavior near a quantum phase transition. Our prediction of a negative magneto-resistance at low temperatures is crucial to understanding the electronic behavior in the vicinity of QPTs. Our work was published in Physical Review Letters 94**,** 037003 (2005). The negative magnetoresistance of thin superconducting films in parallel field was indeed observed in recent experiments. Furthermore, our paper calls for the measurements of the conductivity of quantum wires in the low temperature regime where the negative magneto-resistance, to the best of our knowledge, has not been observed so far.

We plan to investigate the role of strong disorder in quantum phase transitions to explain the recently observed superconducting insulator phase (G. Sambandamurthy et al PRL92, 10705 (2004)). We also plan to develop a non-perturbative technique to study fluctuations in the quantum Ginzburg region. We expect that the magnetoresistance may change sign when approaching the quantum Ginzburg region even at T=0.

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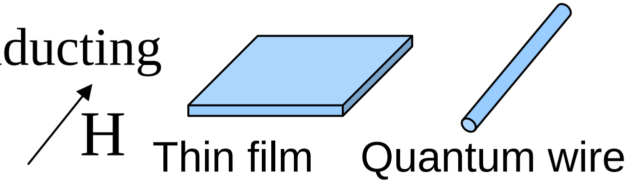
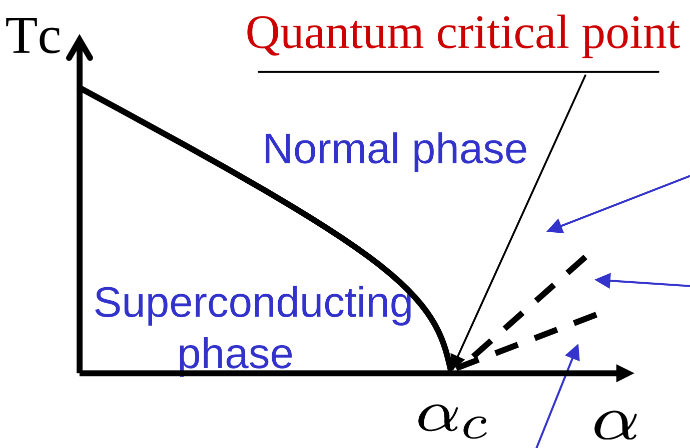
Parallel field tuned superconducting quantum phase transition



Depairing parameter $\alpha \sim H^2$



Classical regime: Singular conductivity behavior, similar to the Aslamazov-Larkin correction

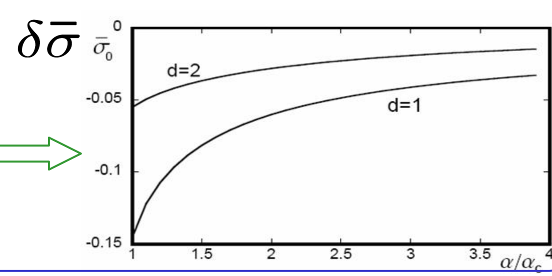
$$\delta\sigma_T(\alpha, T) = e^2 \times \begin{cases} \frac{\sqrt{DT}}{4\sqrt{2}(\alpha-\alpha_c)^{3/2}} & \text{wire} \\ \frac{T}{4\pi(\alpha-\alpha_c)} & \text{film} \end{cases} \quad T > \alpha - \alpha_c$$

Intermediate regime:

$$\delta\sigma_T(\alpha, T) = e^2 \times \begin{cases} \frac{\pi\sqrt{DT^2}}{12\sqrt{2}(\alpha-\alpha_c)^{5/2}} & \text{wire} \\ \frac{T^2}{18(\alpha-\alpha_c)^2} & \text{film.} \end{cases}$$

Quantum regime: Conductivity is almost temperature independent

Conductivity correction at T=0 as a function of the depairing parameter



Future directions:

1. Insulating phase induced by the superconducting correlations.
2. Investigation of the Ginzburg region, role of the disorder.

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